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Executive Summary

This report reviews the available information on Stress Corrosion Cracking (SCC) in liquid and gas pipelines. The information is contained in a number of locations and, although generally consistent in approach, reveals the uncertainty in both the understanding and practical operational methods to effectively prevent, detect, assess, and/or remediate SCC in pipelines. Additional research needs are outlined and prioritized in this regard.

Along with the review of existing information, a questionnaire was circulated to operators, and several detailed operator interviews were conducted. In addition, the applicability of the current regulatory oversight, including Integrity Management (IM) plan review, was considered. A review of procedures for conducting SCC failure investigations was also performed.

Recommendations were made to guide oversight in all areas of the study:

In regard to preventing the initiation of SCC, the single most important recommendation is the emphasis on coatings that remain bonded to the pipe, but allow the passage of CP current in the event of disbondment. Emphasis should also be placed on the QA/QC of the surface preparation and field application. These considerations would apply to both new pipe installation as well as to coating replacement projects. Apart from this consideration, there are limited practical recommendations for pipeline operation processes that can prevent SCC initiation.

In regard to SCC causal factors in pipelines and SCC prediction, the recommendations reflect the technical uncertainty surrounding the subject. Thus, emphasis is placed on written documents in operational and IM plans that stress awareness and the need for additional data collection to enhance understanding. The initial plan produced by an operator may follow several available references to prioritize potential SCC pipe segments and develop a consequent ranking and/or segment risk. However, the emphasis must be such that procedures, especially the collection and integration of data specific to SCC development from ILI and direct examinations, are identified and implemented to refine and update this model over time, which will help operators gain a better understanding of the SCC susceptibility. Therefore, it is recommended that operator plans reflect this need for continued data and knowledge development and sharing.

When SCC is identified, recommendations are made for data collection, data analysis, and planning for further action based on the assessment of the threat to pipeline integrity with an emphasis on written documentation that clearly establishes the decision flow from discovery to field action. Depending on the field conditions, a number of potential mitigation techniques are available and should be considered as alternatives for implementation by an operator. Linking the site-specific SCC data back to the operator linewide model for SCC is recommended for identifying analogous line situations and consequent direct examination needs.

Finally, written contingency plans, such as designation of pre-qualified personnel, data collection requirements, and return to service plans, for in-service failures due to SCC are recommended. Again, any plan should include linking the site-specific data to the operator linewide model for identification of additional potential SCC occurrences.

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1 Introduction

This report has been developed in accordance with the Statement of Work and proposal submitted in response to RFP for Technical Task Order Number 8 (TTO 8), "Stress Corrosion Cracking Study."

1.1 SCC Overview

The pipeline industry and regulatory oversight agencies are well familiar with Stress Corrosion Cracking (SCC). Report No. DTRS56-"Stress Corrosion Cracking Study" by General Physics Corporation was prepared for the Office of Pipeline Safety in May 1999. Based on a study conducted for that report, INGAA reported that SCC accounted for 1.5 percent of the reportable incidents for pipelines within the United States. This was compared to Canadian statistics where 17 percent of the reported failures were attributed to SCC. This magnitude increase in the percentage of failures may lead some to believe that SCC is a more serious problem in Canada than in the United States. However, the report further investigated average incident rates for Canada and the United States for gas transmission pipelines, and found comparable values leading to this/its conclusion:

> "Comparing the incident rates shows that a stress corrosion cracking failure is almost as likely to occur on a gas transmission pipeline within the United States as in Canada. Additionally, the extensive funding provided by pipeline operators for stress corrosion cracking clearly indicates that stress corrosion cracking is a serious pipeline integrity issue of concern to operators of pipelines within the United States. The fact that stress corrosion cracking represents only 1.5 percent of reportable incidents in the United States versus 17 percent in Canada is due to the far greater occurrence of third party damage in the United States."

1.2 SCC in Perspective

At an SCC workshop hosted by OPS in Houston, TX on December 2, 2003, information was presented which included Figure 1-1. The figure indicates that SCC is a relatively small causal factor for gas transmission pipeline incidents in the U.S. However, the frequency of occurrence of SCC relative to other failure causes is higher in Canada. The National Energy Board (NEB) reported that approximately 15 to 20 percent of the failures in Canada were attributable to SCC. The other factors contributing to pipeline failures are being addressed in various research programs, IM initiatives, and regulatory oversight directives in both the gas and liquid pipeline industry. The SCC incident rate is relatively small, yet it is a widespread phenomenon. Moreover, SCC remains a significant issue largely because the industry's understanding of this phenomenon is still evolving and practical methods of addressing SCC are not as mature as methods for addressing other failure causes. Finally, there have been several recent occurrences of SCC failures in the United States, underlining the need for a coherent approach using the knowledge and tools currently available, as well as the need for further research.

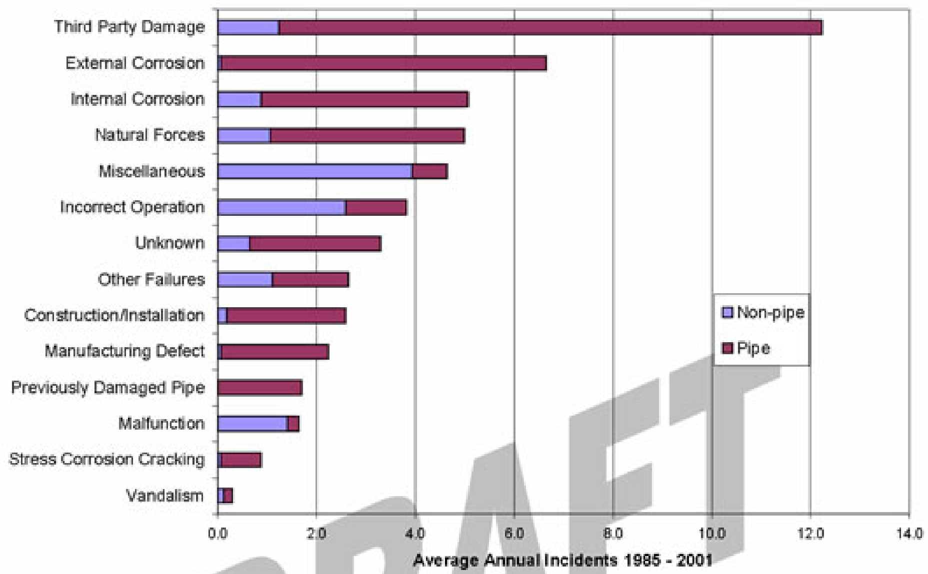

Figure 1-1 **Causes of Gas Transmission Incidents (from OPS Workshop 12/2003)**

2 Background

Recent incidents throughout North America and the world, including Australia, Russia, Saudi Arabia, and South America, have highlighted the threats to pipelines from SCC. In the United States, SCC failures on hazardous liquid pipelines have been less frequent when compared with SCC occurrences on natural gas pipelines. However, three SCC-caused failures of hazardous liquid pipelines have occurred in 2003. Another hazardous liquid pipeline operator has reported finding significant[1] SCC defects.

Figure 2-1 Gas Pipeline SCC

Catastrophic Ruptures, Williams Pipeline, May 1 and December 13, 2003
(http://www.corrosion-doctors.org/Pipeline/Williams-explosion.htm)

Extensive industry research has been conducted related to understanding the mechanism(s) by which SCC affects pipelines and the many factors that pertain to the initiation and growth of SCC. Other research has been performed regarding detection methods, evaluation procedures, and mitigation measures. While much remains to be learned about the factors affecting cracking behavior and methods to detect, evaluate, and mitigate SCC, an understanding is developing within the pipeline industry about how to effectively manage the SCC integrity threat. This industry understanding is being documented by organizations such as ASME and NACE International.

1 A significant stress corrosion crack is defined as one that could potentially fail a hydrostatic test and pose a future integrity threat to the pipeline if not mitigated.

The Research and Special Programs Administration's Office of Pipeline Safety (OPS) issued an Advisory Bulletin on October 2, 2003 that reminds owners and operators of gas transmission and hazardous liquid pipelines to consider SCC as a risk factor when developing and implementing Integrity Management Plans.

2.1 Problem Statement

Federal regulations require pipeline operators to identify and address the range of risks to which pipelines are subjected, including risks associated with SCC. Inspectors need further guidance in determining if operator risk mitigation efforts are adequate. OPS recognizes the need for the industry to develop a standard procedure or procedures to assure SCC issues are handled in a consistent and appropriate manner. OPS also realizes that there is a need for federal inspectors and auditors to have guidance by which to assess the information provided by the various pipeline operators under their integrity programs.

Questions that need to be addressed include:

- What do we already understand about SCC and what do we need to know? (i.e., a knowledge gap analysis)
- Where is SCC found?
- What are the frequency and consequence of SCC-related failures?
- How is SCC detected and characterized?
- What are the susceptibility parameters of SCC?
- What tools exist for detecting SCC and what is their reliability?

To accomplish these goals, RSPA/OPS has requested that a comprehensive study of SCC be completed.

2.2 Project Scope Overview

The scope of the project is to conduct an overall "umbrella" study of SCC issues relating to pipeline integrity for both gas and liquid lines, including the history of SCC, level of risk, indicators of potential for SCC, detection methods, mitigation measures, assessment procedure, and regulatory procedures for evaluation of industry assessments.

The study was comprehensive in scope and involved coordination with major industry trade organizations, pipeline operators, pipeline regulators, and industry experts, both here in the United States and internationally. Known information on the subject of SCC has been assembled or identified, and any gaps in the efforts to understand, identify, assess, manage, mitigate, and regulate enforcement of SCC effects and efforts were identified.

Support of the study by all stakeholders has been critical for the successful outcome of the effort. The study was structured in such a way that public comment period(s) were allowed to ensure the outcome of those publicly reviewed portions of the study would be met with broad acceptance.

2.2.1 Phase 1

The first phase of the study was to prepare for an OPS-hosted SCC workshop held in Houston on December 2, 2003. RSPA/OPS and the National Association of Pipeline Safety Representatives (NAPSR) co-sponsored this workshop on SCC with the pipeline industry trade and technical associations (API, AOPL, INGAA, AGA, PRCI, and NACE International) to provide a forum for the discussion of SCC phenomena in both gas and hazardous liquid pipelines.

In preparation, initial consultation of government and industry contacts was conducted. After the workshop, comments and feedback were incorporated into the draft scope. The study outline was revised as needed in response to feedback provided during and after the workshop; Phase 1 efforts concluded on December 31, 2003.

2.2.2 Phase 2

The following activities were developed for Phase 2 of this study:

- Literature Review: Review existing documentation with regard to SCC history, research conducted to understand the mechanisms causing or contributing to SCC, and prevention, detection and mitigation of SCC.
- SCC Detection, Science, and History: Compile a report summarizing the history of SCC on pipelines, explaining the causes and factors contributing to SCC initiation and growth, and discussing methods for prevention, detection and mitigation of SCC on pipelines, including effectiveness of in-line inspection (ILI) tools and other in-the-bell-hole examination methods to detect SCC.
- Research Gap Analysis: Determine SCC-related R&D issues that warrant further research.
- Application of SCC Principles: Develop a practicable procedure regarding how to assess SCC in operating pipelines within the context of integrity management.
- Regulatory Practices in Foreign Countries: Summarize regulatory practices outside of the United States (i.e., Canada, United Kingdom, Norway, Australia, Russia, Saudi Arabia, and South America).
- Recommended Actions for Operator Response and Remediation: Identify recommended actions to be taken by pipeline operators to facilitate response and assure appropriate remedial measures are implemented following an SCC-related incident.
- Guidelines for Regulatory Response: Develop guidelines for regulatory oversight response in the event of SCC-related incidents.

2.3 Report Outline

As discussed in Chapter 3 of this report, the Literature Review uncovered a large body of documents available on various aspects of SCC. For organization purposes, a database was developed to classify these documents as described in Chapter 3. The understanding of the various aspects of SCC, stemming from the information contained in these documents, is included in following chapters. Note that laboratory research, material testing, and detailed analytical investigations were not a part of this scope.

The understanding of the current knowledge base and associated practices concerning SCC was considered too broad a topic to be summarized in one chapter. Accordingly, this second scope item was broken into four separate chapters – Chapter 4; Understanding Stress Corrosion Cracking (SCC) in Pipelines; Chapter 5, Prevention of an SCC Problem; Chapter 6, Detection of SCC; and Chapter 7, Mitigation of SCC. The regulatory practices in the United States and other foreign countries are discussed in Chapter 8. Chapter 9 concludes the SCC review with a summary of the research needs related to the SCC problem.

Chapter 10 synthesizes the current knowledge base concerning SCC, both from the results of a questionnaire circulated to industry and information from interviews with a number of pipeline operators.

Chapter 11 presents a review of the OPS inspection protocols for an IM plan referencing SCC and discusses guidelines for oversight of the operator responses to these protocols.

Chapter 12 discusses the response to an in-service failure due to SCC.

Chapter 13 is a summary chapter concluding this study.

3 Literature Review

3.1 Scope Statement

"Review existing documentation with regard to SCC history, research conducted to understand the mechanisms causing or contributing to SCC, and prevention, detection and mitigation of SCC."

3.2 Literature Search and Database

A literature search of technical papers, reports, and articles discussing SCC in pipelines was conducted in an attempt to identify the most current and informative documents about understanding and managing SCC. The complete results of the literature review were included in an SCC literature database. This Microsoft Access® database was compiled using a database developed for the OPS from 1998-1999 by General Physics (Hall and McMahon 1999). A few of the reports considered most informative for understanding and managing SCC are discussed in Section 3.3.

A description of the complete database system containing over 300 references is presented in Section 3.4.

3.3 Recommended References

The majority of documentation available focuses on understanding the mechanisms of SCC and conditions conducive to SCC, and is of interest for researchers and others wanting to understand the science of SCC. However, there are a few papers that provide a useful comprehensive overview of understanding and managing SCC, and are valuable for the operator, regulator, and others interested in developing a more general knowledge of SCC.

Perhaps the best of these reports is the *Report of the Inquiry* [on] *Stress Corrosion Cracking on Canadian Oil and Gas Pipelines* by the Canadian National Energy Board (NEB 1996). Composed in 1996, this report is not the most recent; however it is a well-written, readable, and comprehensive piece. Because it specifically addresses issues on Canadian pipelines, the first two chapters are only applicable to this study. While the main focus is on near-neutral-pH SCC, the predominate type experienced in Canada, high-pH SCC is addressed adequately, making this document a very good basic reference, and one that anyone interested in understanding and managing SCC should read.

Another helpful reference is *Stress Corrosion Cracking–Recommended Practices* published by the Canadian Energy Pipeline Association (CEPA 1997a). An effort to revise and update the document is currently underway. This is possibly the only publicly available document that presents "practices" to help operators manage longitudinal, near neutral-pH SCC. While being specifically written to address near neutral-pH SCC, the document is still applicable to all types of pipeline SCC. The document presents an excellent model for pipeline operators who are setting up procedures for preventing, controlling and mitigating external SCC.

CEPA produced an additional report that specifically addresses circumferential SCC, a less common form of SCC (CEPA 1997b). This report documents the experiences of NOVA Gas Transmission

Ltd., Northwestern Limited, Federated Pipe Lines Ltd., and the SNAM system in Italy in investigating and mitigating leaks due to circumferential SCC. Subsequently, CEPA issued an addendum to the *Stress Corrosion Cracking—Recommended Practices* addressing circumferential SCC (CEPA 1998). Circumferential SCC occurs when axial or longitudinal stress, not hoop stress, is the major stress component and is typically associated with ground movement. Circumferential SCC can be classified as either near neutral- or high-pH SCC.

In their report, *Protocol to Prioritize Sites for High pH Stress-Corrosion Cracking on Gas Pipelines*, Eiber and Leis (1998) document the development of a simple form for evaluating the susceptibility of a pipeline segment to high-pH SCC. An example of an SCC integrity management plan is also presented. This document provides detailed descriptions of the variables considered to be vital when determining the degree of susceptibility of a pipeline to high-pH SCC and presents summary level supporting historical data. On the whole, this paper is easy to read and presents good information for use in assessing and managing high-pH SCC.

Another good reference is the recently released NACE International Publication 35103, *External Stress Corrosion Cracking in Underground Pipelines* (NACE 2003). This document contains much of the same information as the NEB report, MH-2-95 (NEB 1996), but also incorporates information learned in the last few years.

3.4 Database Description

The SCC Microsoft Access® database contains basic bibliographic information for over 300 documents, as well as a brief abstract and a number of associated keywords for each report to facilitate searches of the data. Searches can also be performed on the other information contained in the database. Upon entry to the database, the menu shown in Figure 3-1 is displayed, allowing either a general review of the information contained on the database, or the available search options for more specific information.

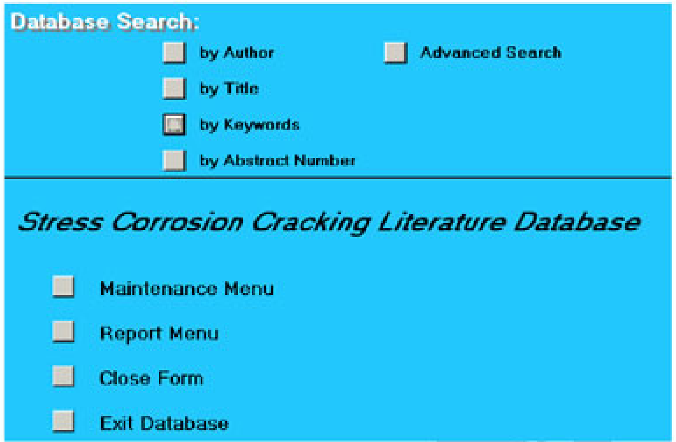

Figure 3-1 Entry Menu to Database

A typical report is displayed in Figure 3-2. The database is not locked, so users can perform their own updates, edits, commenting as desired through a maintenance system, with the menu shown in Figure 3-3.

Stess Corrosion Cracking Database

TITLE	10th International Conference on Pipe Protection (BHR PUB # 7)		
ID	14		
AUTHOR	Wilson, A.		
SOURCE DOCUMENT	10th International Conference on Pipe Protection		
ORGANIZATION	ASME	KEYWORD1	coatings
CATALOG	BHR Publication No. 7	KEYWORD2	pipeline
PROJECT		KEYWORD3	repairs/rehabilitation
ISSN	852988753	KEYWORD4	stresses
		KEYWORD5	sulfide
		KEYWORD6	
DATE	1993		
Abstract Data	Contents: foreword coating systems the development and application of protective pipe coatings for the gas industry in the United Kingdom; selection and experience with different pipeline coatings; the development IN the use of FRE (fiber reinforced epoxy) pipe systems for industrial and offshore application: heat fused polyolefin systems for fusion bonded epoxy coated pipe; novel field joint coating techniques match the latest multi-layer polymeric factor applied coatings; the application of protective coatings over fusion bonded epoxy coatings for the water services in-service behavior of buried zinc coated ductile iron water pipes; a new cement lined sleeve for complete protection of small diameter cement-lined steel pipe joints (pipes up to 22) corrosion, erosion and fire control effect of pressure and flow velocity on sweet corrosion in high pressure horizontal multiphase pipelines; durability of epoxy coating systems under a temperature gradient condition: artificial seaweed controlling pipeline scour-basic investigations and design criteria; the study of sulfide stress cracking on internally coated steel pipe under H2S-H20 environments; durability of polyethylene coated steel pipe at elevated temperature; fire protection of pipes quality assurance and control coal tar enamels-the coating for the future; factors affecting the success of in-situ rehabilitation of high temperature pipelines; information to be gained by the monitoring of the electrical characteristics inherently possed by laminate structured composite pipe components editors: A. Wilson		

Figure 3-2 Typical Document Report from Database

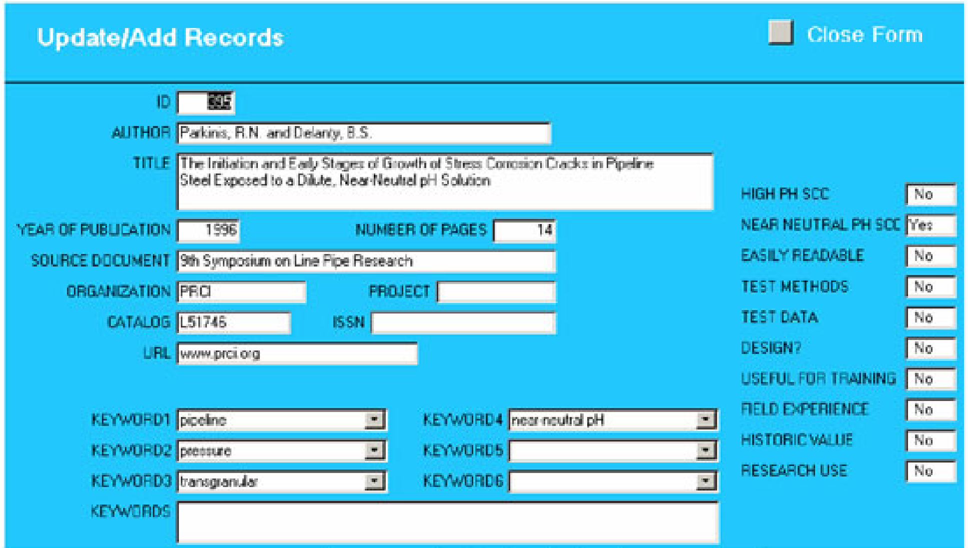

Figure 3-3 Maintenance Menu of Database

3.5 References

(The references listed below are used in this chapter narrative, and are not inclusive of database references).

CEPA. 1997a. *Stress Corrosion Cracking—Recommended Practices*. Canadian Energy Pipeline Association.

CEPA. 1997b. *The CEPA Report on Circumferential Stress Corrosion Cracking. Submitted to the National Energy Board*. Canadian Energy Pipeline Association. December.

CEPA. 1998. *Stress Corrosion Cracking—Recommended Practices. Addendum on circumferential SCC*. Canadian Energy Pipeline Association.

Eiber, R. J., and B.N Leis. 1998. *Protocol to Prioritize Sites for High-pH Stress-Corrosion Cracking on Gas Pipelines*. PRCI. Project PR-3-9403, L51864.

Hall, R.J. and M.C. McMahon. 1999. *Stress Corrosion Cracking Study*. U.S. Department of Transportation, Research and Special Programs Administration, Office of Pipeline Safety. May.

NACE International. 2003. *External Stress Corrosion Cracking of Underground Pipelines*. Publication 35103. Item Number 24221. October.

NEB. 1996. Stress Corrosion Cracking on Canadian Oil and Gas Pipelines. Report of the Inquiry. National Energy Board. MH-2-95. December.

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4 Understanding Stress Corrosion Cracking (SCC) in Pipelines

4.1 Scope Statement

"Compile a report summarizing the history of SCC on pipelines, explaining the causes and factors contributing to SCC initiation and growth, and discussing methods for prevention, detection and mitigation of SCC on pipelines, including effectiveness of ILI tools and other in-the-bell hole examination methods to detect SCC."

The scope statement was broken down into components of Understanding Stress Corrosion Cracking (SCC) in Pipelines (Chapter 4); Prevention of an SCC Problem (Chapter 5); Detection of SCC (Chapter 6); and Mitigation of SCC (Chapter 7).

This chapter summarizes the current state of knowledge of understanding the mechanism and characterization of SCC – both classical (high-pH SCC) as well as near neutral-pH SCC.

4.2 General Characterization (NEB 1996)

SCC in pipelines is a type of Environmentally Assisted Cracking (EAC). EAC is a generic term that describes the formation of cracks caused by various factors combined with the environment surrounding the pipeline. Together these determinants reduce the pressure carrying capacity of the pipe. When water (electrolyte) comes into contact with steel, the minerals, ions and gases in the water create corrosion that attacks the steel. These chemical or electrochemical reactions may result in general thinning, corrosion pits and/or cracks.

EAC includes two mechanisms that should be distinguished: Corrosion fatigue and SCC. "Corrosion fatigue" occurs when chemically reactive agents penetrate fatigue cracks. These agents can accelerate crack progression. The chemical condition within the crack can be more aggressive than on the free surface. Even if the metal surface at the crack tip passivates (forms an inert barrier) the next fatigue loading can crack the brittle deposit and reactivate the whole process. Thus, corrosion fatigue is the joint action of a *cyclic stress and a corrosive environment that decrease the number of cycles to failure*. Compared to the life of the pipe when no corrosion is present, the basic role of the corrosive environment is to decrease the life of the component. Similarly, SCC involves corrosive mechanisms and depends on both an *aggressive environment and tensile stress*. The tensile stress opens up cracks in the material and can be either directly applied or residual in form. Therefore, SCC occurs under sustained tensile loads, while corrosion fatigue occurs under cyclic loading. Appendix A indicates several research areas (see for example Section A.1.2) wherein the difference was difficult to distinguish.

SCC in pipelines is further characterized as "high-pH SCC" or "near neutral-pH SCC," with the "pH" referring to the environment at the crack location and not the soil pH. (pH is the measure of the relative acidity or alkalinity of water. It is defined as the negative log (base 10) of the hydrogen ion concentration. Water with a pH of 7 is neutral; lower pH levels indicate an increasing acidity, while pH levels above 7 indicate increasingly basic solutions.)

The most obvious identifying characteristics of SCC in pipelines, regardless of pH, is the appearance of patches or colonies of parallel cracks on the external surface of the pipe. There may be several of these colonies on a single joint of pipe and many joints of pipe may be involved. The cracks are closely spaced and of varying length and depth. These cracks frequently coalesce to form larger and longer cracks, which in some cases can lead to rupture. If the cracks are sparsely spaced, they might grow through the wall and leak, before they reach a length that is sufficient to cause a rupture.

In order for SCC to occur, three conditions must be satisfied simultaneously. They are listed below and in Figure 4-1:

1. A tensile stress higher than the threshold stress, frequently including some dynamic or cyclic component to the stress;
2. A material that is susceptible to SCC; and
3. A potent cracking environment.

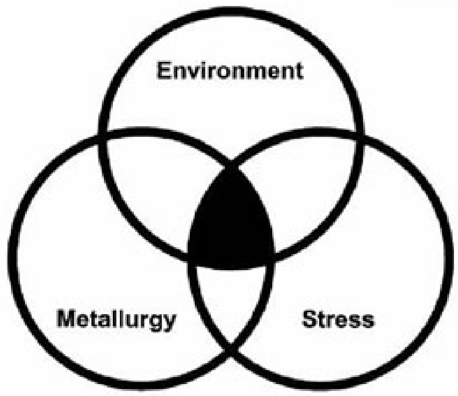

Figure 4-1 Three Conditions Necessary for SCC

SCC cracking is usually oriented longitudinally in response to the hoop stress of the pipe, which is usually the dominant stress component resulting from the internal pressure. However, in some cases (reported as 10 to 20 percent in Canada) SCC also occurs in the circumferential direction (C-SCC) when the predominant stress is an axial stress, such as stresses developed in response to pipe resistance of soil movement, at a field bend, or due to the residual welding stresses at a girth weld (CEPA 1997).

Figure 4-2 SCC Colony on a Large-Diameter, High-Pressure Transmission Gas Pipeline

(http://www.corrosioncost.com/pdf/gasliquid.pdf)

There are two known forms of SCC that have caused failures on pipelines: high pH or "classical" and low pH or "near-neutral pH." These forms are described in more detail in the following sections.

4.2.1 High pH SCC (NEB 1996)

When pipeline steel is exposed to the surrounding environment due to some form of coating failure, it is vulnerable to corrosion. Because soil corrosion is an electrochemical reaction, cathodic protection is used to mitigate corrosion by passing an electrical current through the soil thus giving the pipe a cathodic potential. A concentrated carbonate-bicarbonate (CO_3-HCO_3) solution has been identified as the most probable environment responsible for high-pH SCC. This environment develops as a result of the interaction between hydroxyl ions produced by the cathode reaction and CO_2 in the soil generated by the decay of organic matter. Cathodic protection (CP) causes the pH of the electrolyte beneath disbonded coatings to increase, and the CO_2 readily dissolves in the elevated pH electrolyte, resulting in the generation of the concentrated CO_3-HCO_3 electrolyte. The pH of this electrolyte depends on the relative concentration of CO_3 and HCO_3 and the cracking range is between pH 8 and 11.

The fractured surface of the cracks normally exhibits a dark, discolored coating of oxidized material (primarily magnetite) at the mouth of the crack. The last portion of the pipe wall to fracture, i.e., the rapid fracture region, remains a shiny silver color. The presence of black thumbnail-like flaws on the fracture surface normally indicates that SCC caused the failure.

Analysis of the liquid trapped in the disbonded area or in the crack itself indicates a carbonate-bicarbonate solution with a pH of 8 to 9, or more. Metallographic examination of a section across the crack shows the fracture path to be intergranular, often with small branches, as shown in Figure 4-3. Laboratory simulation with small test specimens indicates that this form of SCC is temperature sensitive and occurs more frequently at higher temperature locations above 100°F. This supports field reports that demonstrate a greater likelihood of SCC immediately downstream of the compressor stations where the operating temperature might reach 150°F.

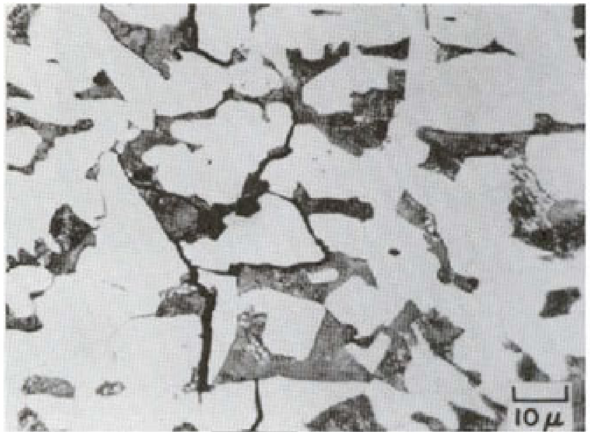

Figure 4-3 An Example of Intergranular Cracking of Pipeline Steel (Revie 2000)

4.2.2 Near neutral-pH SCC (NEB 1996)

This form of SCC was not documented until the late 1970s and was first identified on buried pipelines in Canada where tape-wrapped pipe contained wrinkles in the coating that trapped water with a pH between 5.5 and 7.5. In the case of near neutral-pH SCC, the cracking environment appears to be a diluted groundwater containing dissolved CO_2. The source of the CO_2 is typically the decay of organic matter and geochemical reactions in the soil. This form of cracking occurs under conditions where there is little, if any, CP current reaching the pipe surface, either because of the presence of a shielding coating, a highly resistive soil, or inadequate CP. Typically, the SCC colonies initiate at OD surface locations where there is already pitting or general corrosion, which is sometimes obvious to the naked eye and other times very difficult to observe.

Metallographic examination of near neutral-pH SCC reveals the cracks are predominately transgranular (see Figure 4-4) and are wider (more open) than the high-pH form, i.e. the crack sides have experienced metal loss from corrosion. This morphology implies that the fracture mechanism is different; however, the direct visual appearance of a pipe fracture surface is similar to that of high-pH SCC.

Figure 4-4 Transgranular Cracking in Pipeline Steel (Revie 2000)

4.2.3 Crack Characteristics

There are many similarities between the two forms of SCC. Both occur as colonies of multiple parallel cracks that are generally perpendicular to the direction of the highest stress on the external pipe surface. These cracks can vary in depth and length and grow in two ways. They increase in depth and length and tend to coalesce, or link together, to form longer cracks. At some point these cracks may reach a critical depth and length combination that can result in a rupture. A leak will occur if a crack grows through the pipe wall before it reaches a critical length for rupture. Note that critical size SCCs do not need to fully penetrate the pipe wall for a rupture to occur, i.e., a shallow crack may reach a length that becomes critical. The strength and ductility of the remaining wall determines the critical size at which the crack behavior changes from a slowly growing stress corrosion mechanism to an extremely rapid brittle or ductile stress overload.

The most obvious differences between the two forms are the temperature sensitivity of high-pH SCC, the fracture morphology, and the pH of the pipe environment. The characteristics of high-pH and near neutral-pH SCC are summarized in Table 4.1.